

Evaluation of High-Performance Concrete in Offshore Bridge Monopile Foundations

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Abstract

This study evaluates the use of high-performance M60 concrete in large-diameter monopile foundations for marine bridge construction, with particular emphasis on Ground Granulated Blast-Furnace Slag (GGBS), constructability, compressive strength, durability-oriented quality control, and field load-test performance. The study is based on laboratory trials and field observations from a coastal bridge project in Mumbai, where 2500 mm and 3200 mm diameter monopiles were used. Six initial test piles and 99 working piles were considered across Amarsons Garden Interchange (AGI), Haji Ali Interchange (HAI), and Main Line Bridge (MLB). Three GGBS-modified mixes, designated TM-205, TM-206 and TM-207, represented approximately 40%, 45% and 50% GGBS replacement levels within the cementitious system. The selected TM-207 mix contained 320 kg/m³ OPC, 350 kg/m³ GGBS, 30 kg/m³ micro-silica, 168 kg/m³ water, 464 kg/m³ of 20 mm aggregate, 461 kg/m³ of 10 mm aggregate, 195 kg/m³ C-sand, 453 kg/m³ washed sand, and a reported water-to-cementitious ratio of 0.24. Trial flow values for five mixes ranged from 620 to 640 mm. For a reported TM-207 28-day cube test, the four individual strengths were 77.05, 75.69, 75.61 and 76.29 MPa, with an average of 76.27 MPa. Field verification included bidirectional static load testing, lateral load testing, instrumentation using load cells, vibrating-wire strain gauges and in-place inclinometers, Cross-Hole Sonic Logging (CHSL), and high-strain dynamic pile testing. The lateral test on a 2500 mm diameter pile reached 650 MT (6527 kN), while the working-load displacement at scour level was reported as 10.91–14.30 mm, below the cited 25 mm criterion. The study also identifies practical construction problems, including concrete segregation, tremie choking, borehole collapse and localized CHSL anomalies. Overall, the results demonstrate that a GGBS-rich M60 mix can satisfy the reported strength and constructability requirements when accompanied by stringent material control, concrete placement control and integrated non-destructive/field testing.

Keywords: high-performance concrete; M60 concrete; GGBS; monopile foundation; marine bridge; durability; CHSL; lateral load test; pile integrity; quality control

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1. Introduction

Marine and nearshore bridge foundations are exposed to a combination of structural, geotechnical and environmental demands. Large-diameter monopiles provide a compact foundation arrangement in which a single cylindrical pile transfers vertical and lateral actions into the surrounding ground. The source project adopted monopile foundations for a coastal road/bridge system in Mumbai, with 33 marine modules executed using monopile foundations instead of conventional group piles. The reported pile diameters were 2500 and 3200 mm, with M60 concrete and Fe-550D reinforcement.

The concrete used in a monopile is not required only to achieve a specified compressive strength. It must also remain workable during long-duration placement, maintain continuity through tremie concreting, resist chloride- and sulphate-related exposure, and provide adequate bond and durability around reinforcement and steel liner systems. The study therefore combines concrete mix development with field-scale foundation testing and pile-integrity verification.

A central material modification investigated in the study is the partial replacement of Portland cement with GGBS. The thesis considered replacement levels of approximately 40%, 45% and 50% of the cementitious system, while keeping other major variables controlled. The motivation was to reduce cement consumption while maintaining or improving long-term performance and lowering the material-related environmental burden.

2. Research Objectives

- a) To develop and evaluate an M60 high-performance concrete mix suitable for large-diameter marine monopile foundations.
- b) To examine the effect of GGBS replacement on strength, workability and durability-oriented quality indicators.
- c) To establish a field quality-control framework combining laboratory concrete tests and pile-integrity/load testing.
- d) To evaluate the axial and lateral response of instrumented monopile test piles under proof loading.
- e) To document construction-related problems and identify practical controls for reliable monopile concreting and testing.
- f) To assess the economic and environmental rationale for using GGBS in the selected M60 concrete system.

3. Project and Foundation Characteristics

The field investigation covered AGI, HAI and MLB locations. The study reports 99 working monopiles: 32 piles of 2500 mm diameter at AGI, 50 piles of 2500/3200 mm diameter at HAI,

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and 17 piles of 3200 mm diameter at MLB. Monopile socketing lengths varied with ground conditions. AGI, where basaltic rock outcrops were encountered, had reported socketing lengths of 4.0–11.8 m. HAI had 6.0–12.25 m, while MLB had 5.35–15.70 m.

Location	Diameter (mm)	No. of working piles	Reported ground condition / socketing
AGI	2500	32	Basalt outcrop; 4.0–11.8 m
HAI	2500 & 3200	50	Slush/loose soil and weathered rock; 6.0–12.25 m
MLB	3200	17	Slush/loose soil/weathered rock; 5.35–15.70 m

Table 1. Working-pile distribution and reported foundation conditions, compiled from the uploaded thesis.

4. Materials and Mix Development

The selected concrete system comprised OPC, GGBS, micro-silica, natural/fractionated sands, coarse aggregates, chemical admixture, corrosion inhibitor and water. The source specifies quality requirements for cement, GGBS, micro-silica, chemical admixtures and reinforcement. For example, the reported GGBS requirements included minimum 85% glass content, minimum Blaine fineness of 275 m²/kg, maximum 1% moisture and maximum 0.1% chloride content.

Mix	Cement (kg/m ³)	GGBS (kg/m ³)	Micro-silica (kg/m ³)	Water (kg/m ³)	w/cm reported
TM-205	390	280	30	168	0.24
TM-206	355	315	30	168	0.24
TM-207	320	350	30	168	0.24

Table 2. Principal cementitious proportions of the GGBS-modified trial mixes.

The final M60 composition reported for monopile concrete was 320 kg/m³ OPC, 350 kg/m³ GGBS, 30 kg/m³ micro-silica, 168 kg/m³ water, 464 kg/m³ 20 mm aggregate, 461 kg/m³ 10 mm aggregate, 195 kg/m³ C-sand, 453 kg/m³ washed sand, 7.70 kg/m³ admixture and 0.125 kg/m³ corrosion inhibitor. The corresponding reported water-to-cementitious ratio was 0.24.

Ingredient	Quantity (kg/m ³)
OPC (Type V)	320

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GGBS	350
Micro-silica	30
Water	168
20 mm aggregate	464
10 mm aggregate	461
C-sand	195
Washed sand	453
Admixture	7.70
Corrosion inhibitor	0.125

Table 3. Reported composition of the selected M60 monopile mix.

5. Experimental and Field Methodology

5.1 Laboratory concrete programme

Concrete specimens were prepared using $150 \times 150 \times 150$ mm cubes for compressive strength, 150×300 mm cylinders for split tensile strength, and $150 \times 150 \times 700$ mm prisms for flexural testing. Mixing was performed in a ribbon/pan-type mixer operated below half of its rated capacity. The reported procedure consisted of pre-buttering, staged introduction of aggregates and cementitious materials, one minute of dry mixing, followed by approximately 3–4 minutes of wet mixing. Specimens were compacted using a table vibrator, kept in moulds for 24 hours and subsequently water cured. Testing ages included 7, 28 and 56 days.

5.2 Workability and durability-oriented testing

Fresh concrete flow was measured for trial mixes. Five reported flow values were 630, 620, 635, 640 and 630 mm. The study also describes rebound hammer, penetration resistance, ultrasonic pulse velocity, pullout testing, drilled cores, wireless maturity monitoring, rapid chloride permeability testing (RCPT) and water permeability testing as components of the concrete quality-evaluation framework.

Trial mix	Flow (mm)
M1	630
M2	620
M3	635
M4	640
M5	630

Table 4. Reported flow-test results.

5.3 Monopile construction sequence

Initial test piles were constructed using Reverse Circulation Drilling (RCD). Temporary outer casing/liners were used because of reclaimed-ground conditions. The sequence comprised pit

preparation, liner positioning and driving using a two-legged vibro-hammer, RCD drilling, reinforcement-cage installation, instrumentation installation, tremie preparation and underwater concreting. The source reports use of 350 mm internal-diameter tremie pipe, with the tremie maintained inside the concrete during withdrawal.

For the working piles, 54 mm diameter sonic tubes were installed for CHSL: eight tubes in 2500 mm piles and ten tubes in 3200 mm piles. The 99 working piles were constructed between 27 December 2022 and 5 March 2023, with a reported production rate of approximately one pile every four days.

5.4 Bi-directional static load testing

O-cell bi-directional static load testing was planned after 28 days of concrete placement or after achieving the design cube strength, whichever occurred earlier. The O-cell mobilizes resistance in opposite directions, allowing separate assessment of upper-shaft and lower-shaft/base resistance. The source reports planned test loads of 5000 MT for 2500 mm monopiles and 10500 MT for 3200 mm monopiles.

In the reported test series, the bidirectional tests showed small movements, with one MPV2 test stopped after a maximum unidirectional load of 2576 MT. The source states that the observed bearing-plate displacements were less than 5 mm and that the available results did not require extrapolation of the bidirectional plots.

5.5 Lateral load testing and instrumentation

A 2500 mm diameter test pile with a reported embedded length of 19.65 m was subjected to lateral proof loading. The working lateral load was 350 MT and the target test load was 700 MT. Instrumentation comprised hydraulic jacks, load cells, LVDTs, vibrating-wire strain gauges and two in-place inclinometer strings.

The test pile ultimately sustained 650 MT (6527 kN). At the cited working-load stage of 3327 kN, scour-level displacements from the two inclinometer strings were 10.91 and 14.30 mm. The thesis compares these values with an IRC-based 25 mm criterion at scour level. At 650 MT, the displacement at the load-application level was approximately 103.81 mm by LVDT, with IPI readings of 100.45 and 104.75 mm.

5.6 Cross-Hole Sonic Logging and PDA

CHSL was carried out on all working piles, generally about seven days after concreting, using the access tubes installed in the cages. The procedure records first-arrival time and signal energy along the pile depth. The source classifies integrity using the increase in first-arrival time (FAT) and energy reduction. Reported classification bands were: satisfactory/good for FAT increase of

0–10% and energy reduction below 6 dB; minor defect for 11–20% and below 9 dB; poor/ flaw for 21–30% and 9–12 dB; and poor/defect for greater than 31% and greater than 12 dB.

High-strain dynamic testing followed ASTM D4945 as described in the thesis. The test used controlled hammer impacts, beginning at approximately 0.5 m drop height and increasing the drop height in increments. Strain transducers and accelerometers were used to obtain real-time response data.

6. Results and Discussion

6.1 Effect of GGBS replacement

The trial programme moved from mixes containing fly ash to GGBS-modified mixes. TM-205, TM-206 and TM-207 corresponded to 40%, 45% and 50% GGBS replacement levels as described in the source. The final selected TM-207 composition used 320 kg/m³ cement and 350 kg/m³ GGBS. This represents a GGBS-rich binder system and substantially reduces the quantity of Portland cement relative to the earlier trial mixes.

The thesis reports that the selected mix satisfied the specified compressive-strength and workability criteria. A documented 28-day TM-207 cube-test sheet reports four individual values of 77.05, 75.69, 75.61 and 76.29 MPa, corresponding to an average of 76.27 MPa. These values are above the nominal M60 characteristic strength by approximately 15–28%, although the paper does not treat this single test sheet as a substitute for a complete statistical strength dataset.

Specimen	28-day strength (MPa)
1	77.05
2	75.69
3	75.61
4	76.29
Average	76.27

Table 5. Reported 28-day TM-207 compressive-strength result.

6.2 Workability

Flow values between 620 and 640 mm demonstrate that the trial mixes were capable of producing a high-flow concrete suitable for the placement environment during the laboratory trials. However, field observations reveal that laboratory workability alone did not guarantee uninterrupted placement. After several piles, the concrete was reported to develop a rubbery texture, with aggregate settlement and tremie choking occurring within approximately 15–20 minutes during some pours. This highlights the importance of retention of workability and stability, rather than considering initial flow alone.

6.3 Lateral response

The lateral test demonstrated a measurable increase in displacement with increasing applied load. At the working-load stage, the reported scour-level displacements of 10.91–14.30 mm were below the 25 mm limit cited from IRC 78 in the thesis. At the maximum reported applied load of 650 MT, the load-application-level displacement reached approximately 103.81 mm by LVDT, while the two IPI strings measured 100.45 and 104.75 mm. The close agreement between the independent LVDT and inclinometer measurements provides confidence in the displacement monitoring arrangement.

The strain-gauge and inclinometer profiles also provide information on curvature and deformation along the pile. The thesis notes that very small strains were measured in the liner-zone gauges, while deeper gauges showed progressively greater response under increasing lateral load. This confirms the value of distributed instrumentation compared with a single pile-head displacement measurement.

6.4 Axial load-transfer behaviour

The bidirectional static load results indicated limited displacement in the tested monopiles and substantial mobilization of shaft resistance before the toe response became dominant. For the reported ultimate test stage, the mobilized end-bearing stress was calculated as 3.17 MPa, corresponding to a calculated end-bearing load of approximately 1558 MT. The thesis explicitly cautions that this is mobilized rather than ultimate end-bearing resistance and that additional toe movement could mobilize further resistance.

6.5 Integrity assessment and construction anomalies

CHSL provided an important quality-assurance layer because the piles were cast in difficult conditions. In some early tests, hazy signals appeared in longer sonic-tube corridors while adjacent tubes were satisfactory. Where the pattern persisted, cores were extracted. Some cores showed continuous breakage at the same depths identified in the CHSL reports, and subsequent investigations indicated weak concrete/honeycombing at those locations. Remediation included epoxy and microfine grout, and in selected cases insertion of 32 mm diameter reinforcement followed by grouting.

These observations show that pile integrity cannot be inferred from compressive strength of companion cubes alone. A pile may achieve adequate laboratory strength while still containing localized construction defects caused by segregation, contamination, poor tremie continuity, borehole instability or concrete placement problems.

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6.6 Construction-related findings

Observed issue	Reported cause / manifestation	Control implication
Concrete segregation	Watery/rubbery texture; aggregate settlement	Control mix stability, transport time and admixture compatibility
Tremie choking	Concrete reportedly choked tremie within 15–20 min in some pours	Maintain continuous placement; contingency tremie set; monitor concrete rheology
Borehole collapse	Three reported collapses at HAI/MLB; liner not driven sufficiently	Verify liner toe and ground stability before drilling
Concrete loss at liner toe	Gap between liner toe and surrounding bedrock	Use underwater inspection, sandbags and controlled concreting strategy
CHSL anomalies	Hazy signals and confirmed weak/honeycombed zones in some cases	Use CHSL with coring/televviewer/hydro-jetting where required

Table 6. Principal construction and quality-control observations reported in the thesis.

6.7 Economic and environmental implications

The source argues that GGBS replacement can reduce the cement requirement and therefore the material cost of M60 concrete while supporting durability in aggressive exposure. The selected TM-207 system uses 350 kg/m³ GGBS against 320 kg/m³ OPC. The study also reports a total testing expenditure of Rs 3,525,560 for the listed inspection and testing programme.

Because the uploaded thesis does not provide a complete life-cycle carbon calculation or a full comparative bill of quantities for an all-OPC alternative, the environmental and economic conclusions should be stated as project-level observations rather than as quantified life-cycle savings.

7. Quality-Control Framework Proposed from the Study

Based on the combined laboratory and field evidence, the quality evaluation of marine monopile concrete should be treated as a multi-stage process: (i) source approval of cementitious materials and aggregates; (ii) trial-mix verification; (iii) fresh-concrete control; (iv) cube-strength verification; (v) durability-oriented testing; (vi) placement monitoring; (vii) pile integrity testing; and (viii) targeted investigation and remediation of anomalies.

Stage	Recommended control	Evidence in study
Materials	Source-wise chemical/physical	Material specification tables

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	acceptance	
Mix design	GGBS level, w/cm, admixture compatibility	TM-205/TM-206/TM-207 trials
Fresh concrete	Flow/workability, temperature, stability	Flow results + field observations
Strength	7/28/56-day compressive strength	Cube programme; TM-207 28-day result
Durability	RCPT, water permeability, chloride-related tests	Specified in testing programme
Placement	Tremie continuity, concrete level, overflow and time control	Field construction observations
Integrity	CHSL, coring where required, optical televiewer/hydro-jetting	Working-pile QA programme
Structural response	Static/lateral/PDA testing and distributed instrumentation	Test-pile programme

Table 7. Integrated quality-control framework derived from the study.

8. Conclusions

The investigated M60 monopile concrete used a high proportion of GGBS and micro-silica. The selected TM-207 mix contained 320 kg/m³ OPC, 350 kg/m³ GGBS and 30 kg/m³ micro-silica at a reported w/cm ratio of 0.24.

The reported flow of the five trial mixes ranged from 620 to 640 mm, indicating high-flow characteristics appropriate to tremie placement, although field behaviour showed that flow retention and segregation resistance require separate control.

A documented TM-207 28-day cube-test set produced an average compressive strength of 76.27 MPa from four reported specimens, indicating that the selected mix exceeded the nominal M60 characteristic strength in that reported test.

The bidirectional static load tests showed small measured movements in the reported cases, while the lateral test pile sustained 650 MT (6527 kN). At the reported working-load stage, scour-level displacement was 10.91–14.30 mm against the 25 mm criterion cited in the source. Distributed instrumentation using LVDTs, load cells, strain gauges and in-place inclinometers provided mutually consistent measurements and allowed the pile deformation profile to be evaluated along depth.

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CHSL proved valuable for identifying possible local defects that were subsequently investigated using coring and other methods. This demonstrates that structural quality of cast-in-place monopiles requires both material testing and in-situ integrity testing.

Field construction experience identified concrete segregation, tremie choking, borehole collapse and local concrete defects as important risks. These risks can be reduced through strict control of liner installation, drilling stability, concrete rheology, tremie continuity and inspection procedures.

The study supports the practical use of GGBS-rich M60 concrete for marine monopiles, but quantified life-cycle carbon savings and statistically complete comparative performance datasets would be required before making broader generalizations.

9. Limitations and Scope for Further Research

The present manuscript is deliberately restricted to information supported by the uploaded thesis. The source contains a broad discussion of monopile behaviour, but its abstract also includes a separate cyclic-loading/finite-element discussion involving sandy soil and scaled monopiles that is not directly aligned with the detailed M60 concrete field programme. That material has therefore not been used as evidence for the concrete-performance conclusions of this paper.

Future work should include a larger statistically structured dataset for strength development at 7, 28 and 56 days; direct comparison of GGBS replacement levels under identical curing conditions; quantified chloride diffusion/transport data; systematic temperature and slump-flow retention monitoring; full correlation of CHSL anomalies with core strength and permeability; and life-cycle assessment comparing GGBS-rich and conventional cementitious systems.

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